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# SOUTHERN COSMOLOGY SURVEY III: QSO'S FROM COMBINED GALEX AND OPTICAL PHOTOMETRY

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## ABSTRACT

We present catalogs of QSO candidates selected using photometry from GALEX combined with SDSS in the Stripe 82 region and Blanco Cosmology Survey (BCS) near declination −55 degrees. The SDSS region contains $\simeq 700$ objects with magnitude $i < 20$ and $\simeq 3600$ objects with $i < 21.5$ in a $\simeq 60$ square degree sky region, while the BCS region contains $\simeq 280$ objects with magnitude $i < 20$ and $\sim 2000$ objects with $i < 21.5$ for a 11 square degree sky region that is being observed by three current microwave Sunyaev-Zeldovich surveys. Our QSO catalog is the first one in the BCS region. Deep GALEX exposures ( $\gtrsim 2000$ seconds in $F_{UV}$ and $N_{UV}$, except in three fields) provide high signal-to-noise photometry in the GALEX bands ($F_{UV}, N_{UV} < 24.5$ mag). From this data, we select QSO candidates using only GALEX and optical $r$-band photometry, using the method given by Atlee and Gould (2008). In the Stripe 82 field, 60% (30%) of the GALEX selected QSO's with optical magnitude $i < 20$ ($i < 21.5$) also appear in the Richards et al. (2008) QSO catalog constructed using 5-band optical SDSS photometry. Comparison with the same catalog by Richards et al. shows that the completeness of the sample is approximately 40%(25%). However, for regions of the sky with very low dust extinction, like the BCS 23hr field and the Stripe 82 between 0 and 10 degrees in RA, our completeness is close to 95%, demonstrating that deep GALEX observations are almost as efficient as multi-wavelength observations at finding QSO's. GALEX observations thus provide a viable alternate route to QSO catalogs in sky regions where $u$-band optical photometry is not available. The full catalog is available at `http://www.ice.csic.es/personal/jimenez/PHOTOZ`.

*Subject headings:* cosmology: early universe - cosmology: theory - galaxies: intergalactic medium - atomic processes

## 1. INTRODUCTION

With ground-based telescopes surveying the sky at millimeter wavelengths and angular resolutions of around 1 arcminute (APEX[6], SPT[7], ACT[8]), and the the launch of the Planck satellite, we will be soon exploring how structures grew in the universe using the Sunyaev-Zeldovich effect (Sunyaev & Zeldovich 1972). Indeed, the SPT collaboration has recently released its first results of their blind survey (Staniszewski et al. 2008). However, microwave fluctuation power spectrum at angular scales smaller than 4 arcminutes will be dominated by point source emission at all frequencies. It is therefore imperative to understand the point-source contamination of the primordial and secondary power spectrum of the cosmic microwave background if we aim to extract cosmological information from small-scale microwave fluctuations.

One of the major point-source contaminants is Quasars (QSOs). The Sloan Digital Sky Survey (SDSS) has revolutionized the QSO field by providing a photometric method to detect QSOs over large areas of the sky (Richards et al. 2004, 2008). However, the SDSS only covers 25% of sky, most of it in the northern hemisphere, and all of the ground-based high-resolution Sunyaev-Zeldovich experiments primarily observe the southern hemisphere. Clearly a good photometric technique that relies on a small number of filters would be useful for identifying and removing QSO point sources. Because most future surveys will lack $u-$band photometry,[9] the SDSS technique cannot be used and one needs to rely on other photometric surveys.

Recently, Atlee & Gould (2007) proposed a method to discover QSOs using the Galaxy Evolution Explorer (GALEX) bands in combination with only one other photometric band (e.g., $r$). Because GALEX will eventually cover the whole sky, this provides the means to construct a catalog of QSOs in the regions covered by the future SZ experiments. This technique is similar to that proposed by Bianchi et al. (2007, 2005) but with the difference that Bianchi et al. exploit the superior photometric and morphological information of the SDSS sample, thus requiring costly multiwavelength photometry. Our GALEX Legacy program, part of the Southern Cosmology Survey (SCS) program, provides the largest continuous area and deepest coverage to date with overlapping optical data (the SDSS Stripe 82 field and Blanco Cosmology Survey 23-hour field). Exploiting this data set, we have used the Atlee & Gould (2007) technique to construct a QSO catalog in these two fields. We are the

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[6] Atacama Pathfinder Experiment; www.apex-telescope.org
[7] South Pole Telescope; spt.uchicago.edu
[8] Atacama Cosmology Telescope; www.physics.princeton.edu/act

[9] One notable exception is LSST (www.lsst.org), but science operations will not take place until 2016.

first ones to provide a QSO catalog for the BCS 23-hour field. All three ground-based microwave experiments are observing the 23-hour field, while ACT is observing Stripe 82. We have found in the SDSS Stripe 82 and BCS areas around 1000 (5500) QSO candidates for $i < 20$ ($i < 21.5$). For the brighter sample, around 60% of our QSO candidates are actual QSO's, as determined by comparison with SDSS-identified QSOs from the Richards et al. catalog, dropping to around 30% for the fainter sample. The sample is complete at the 40% and 25% level in the brighter and fainter samples, respectively, when compared to the QSOs in the Richards et al (2008) catalogue[10]. Our completeness is significantly higher $\sim 95\%$ for regions of the sky with very low dust extinction. We provide an electronic version of the QSO catalogs at `http://www.ice.csic.es/personal/jimenez/PHOTOZ`.

## 2. INPUT CATALOGS

Our GALEX observations comprise a Legacy program awarded in Cycle 3, with the goal of mapping 100 deg$^2$ with 3 ks exposure time per pointing in both the $F_{UV}$ and $N_{UV}$ filters. We chose to map roughly 11 deg$^2$ covering the Blanco Cosmology Survey[11] (BCS) 23-hour field at declination -55°, and a larger area of the equatorial Stripe 82 field covered by SDSS. Both areas have *griz* optical observations, and SDSS also has *u* observations. We took advantage of the fact that the Stripe 82 survey area includes a number of the GALEX Medium Imaging Survey (MIS) fields, which already had many observations of 1.5 ks or longer, and therefore needed only partial additional observations to reach our 3 ks target. When our program is finished, we will have collected around 210 ks of new GALEX observations.

Matches between the GALEX detections and SDSS or BCS data were done by initially assigning optical sources to a particular GALEX pointing if they fall within 35.1′ of the GALEX field center. This cuts the noisiest region of the GALEX fields (near the edges), while maintaining complete sky coverage between neighboring fields (i.e. leaving no gaps). Within every GALEX field, each optical source is assigned a match to the nearest GALEX object detected in the $N_{UV}$ band, if the GALEX object is within a 4″ radius of the optical source; this is a relatively conservative matching radius (Agüeros et al. 2005). After all sources in the field are assigned, the combined catalog is searched to test whether any two optical sources are assigned to the same GALEX object. In the case of overlapping assignments, the closest optical source to the GALEX position is selected and the other is removed from the catalog. Optical sources which do not have a GALEX detection are removed from the catalog.

Because of the differences in the point spread functions of different instruments and between bands, simple aperture photometry is not appropriate for this study. The SDSS point spread function widths are approximately 1.5″ and vary with sky brightness (Abazajian et al. 2003), while GALEX point spread function widths vary across the field between roughly 4″ and 7″ (Morrisey et al. 2005). Our approach is to use AB magnitude measures that are as close as possible to the total

[10] `www.physics.drexel.edu/~gtr/outgoing/nbckde/tab1.dat.bz2`
[11] cosmology.uiuc.edu/BCS

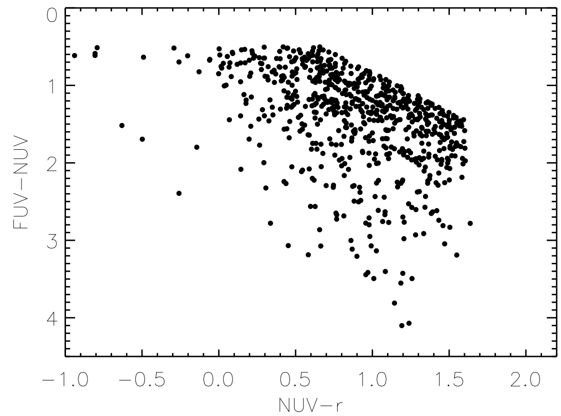


FIG. 1.— GALEX-selected QSO candidates in the SDSS Stripe 82 sky region with magnitude $i \leq 20$, in a color-color plot after Atlee & Gould (2007) cuts (see Table 1) have been applied.

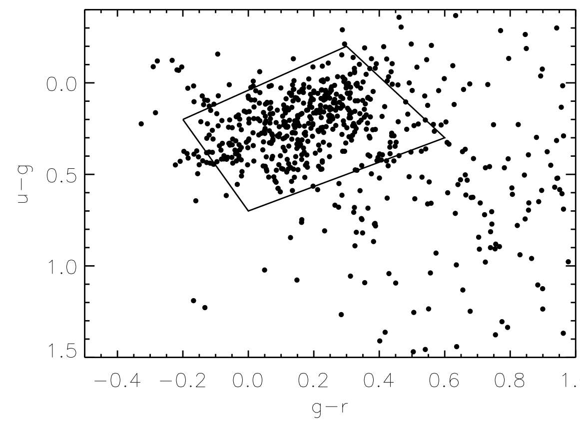


FIG. 2.— QSO candidates from Fig. 1 displayed in the $u-g$ vs. $g-r$ plane. The area delineated by the solid lines is the Richards et al. (2004) most likely locus for QSO selection in the SDSS. Note that about 20% of the GALEX-selected QSO candidates are outside the Richards et al. area. For the fainter sample, the plot is similar but with a larger number of outliers (around 40%).

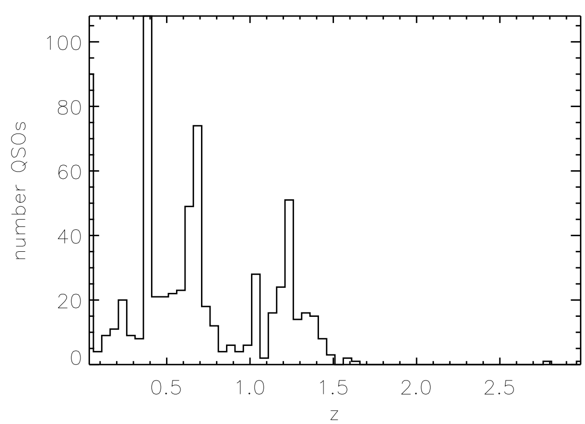


FIG. 3.— Redshift distribution of QSO candidates in Fig. 1. Note that about 13% of the candidates are flagged as stars, including most of the outliers in Fig. 2.

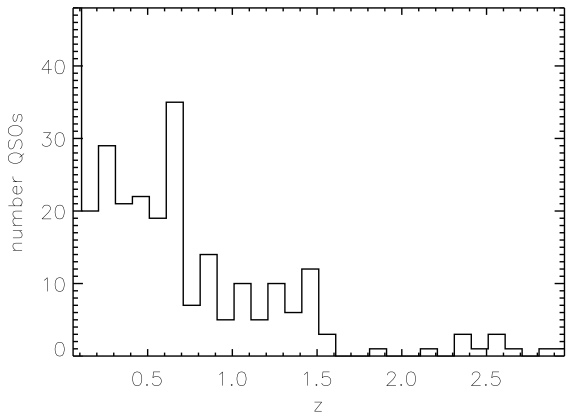


Fig. 4.— Redshift distribution of GALEX-selected QSO candidates in the BCS 23-hour region with magnitude $i < 20$. About 20% of the candidates are flagged as stars.

TABLE 1
Color criteria from Atlee & Gould (2007) used in the present study

| Boundary Criterion |
|---|
| FUV-NUV ≥ 37.314 (NUV-R) - 70.70372 |
| FUV-NUV ≥ (NUV-R) - 0.5 |
| NUV - R ≥ -0.895 |
| FUV-NUV ≥ 0.5 |
| FUV - NUV ≤ 4.343 |

flux emitted by the galaxy in each band. For the SDSS data we use C-model magnitude measurements, which consist of fitting models to a galaxy profile composed of an exponential disc plus a deVaucouleurs profile; if an object is a point source, the exponential profile should dominate and give a good magnitude measurement. These fits are integrated to three and seven times the characteristic radius, at which point the function is truncated to smoothly go to zero. The two fits are weighted based on the quality of the fit and combined to obtain the best-fitting profile.[12] This measurement provides our estimate of the total photometry for each SDSS band.

For the BCS, we use the catalog developed by Menanteau et al. (2008). In this case the optical magnitudes are obtained using the `magauto` feature in SExtractor [13], providing a good estimate of the total photometry for each BCS band. Note that $r-$band magnitudes in BCS differ only by $\sim 0.03$ mag. from the SDSS $r-$band, which makes no difference in the QSO photometric selection.

## 3. CATALOG CONSTRUCTION AND DESCRIPTION

We construct our catalog of QSO candidates by using the selection criteria of Atlee & Gould (2007) described in their Table 1 and Section 3, which we repeat here in our Table 1. Figure 1 shows the QSO candidates in the $F_{UV} - N_{UV}$ vs. $N_{UV} - r$ color-color plot for the Stripe 82 region. After all selection cuts have been applied, we are left with a catalog of $\simeq 1000$ objects for a magnitude cut of $i < 20$. Because we have SDSS photometry for all candidates, we can compare with the catalogue from Richards et al. (2008). We match the two catalogues by finding matches within a 1.5" radius of each object in the Richards et al. catalog. We find that every object from our catalogue matches to only one Richards et al. object. As a function of magnitude we find that for $i < 19.1$ about 70% of our QSO candidates are in the Richards et al. catalogue. This ratio decreases to 60% for $i < 20$ and 30% for $i < 21.5$. Using these numbers we conclude that the catalogs are complete with respect to the Richards et al. sample at the 40% up to $i < 20$ and 25% for $i < 21.5$. Because the GALEX observations are significantly influenced by diffuse dust extinction, we explore the completeness for regions in Stripe 82 with the lowest dust extinction. The lowest extinction region is in the range $0 <$ RA $< 10$. In this region we find 95% matches for $i < 21.5$ and a similar completeness level when compared to the Richards et al. catalogue. This demonstrates that our technique is as successful as optical multi-wavelength searches in low extinction regions of the sky.

To illustrate graphically the success of our scheme, we compare with the most likely color-color selection by Richards et al. (2004), which has proven very successful at photometrically finding QSOs. This is shown in Fig. 2. The locus that Richards et al. (2004) use to select QSO candidates is enclosed by the solid lines. Objects that fall within this region are more than 95% likely to be true spectroscopically confirmed QSOs (Richards et al. 2004). For a magnitude cut of $i < 20$ (21.5) we find that only 20% (40%) of our objects lie outside the Richards-defined QSO region. Because we can compute accurate photometric redshifts using the GALEX and optical bands as done in Niemack et al. (2008), we can test how many of our candidates are at $z = 0$ and are therefore likely stars. We show the redshift distribution and spatial distribution of the QSO candidates in Fig. 3 and 5, for the Stripe 82 and BCS 23-hour regions respectively. Between 13% and 20% of the QSO candidates are likely stars; they all lie outside the Richards region.

Our success rate at detecting QSOs is higher than Atlee & Gould (2007) because we have deeper GALEX exposures ($\gtrsim 2000$ seconds, except in three fields, which is 20 times longer than the GALEX all-sky-survey they used), which allow for better sampling of the QSO emission features in the otherwise power-law-like UV spectrum of the QSO's. In particular we find that at the bright end ($i < 19.1$) our technique finds 100% of the QSOs of Richards et al. catalog. For dimmer samples the success rate is lower, as more and more QSO's are not detected in the GALEX bands, especially in the $F_{UV}$. We interpret this as an effect of extinction: the Richards et al. QSO missing from the GALEX selection are redder in the UV.

For the BCS sample we do not have $u$-band optical data, so we directly apply the cuts from Table 1 and present the redshift distribution and location of these host in Fig. 4 and 5. As expected and discussed by Richards et al. (2004), we are selecting QSOs at $z < 2$. This can be seen in both Figs. 3 and 4. The BCS catalogs contain $\sim 280$ objects with magnitude $i < 20$ and $\sim 2000$ objects with $i < 21.5$ for a 11square degree region. The

[12] www.sdss.org/dr5/algorithms/photometry.html
[13] `http://terapix.iap.fr`

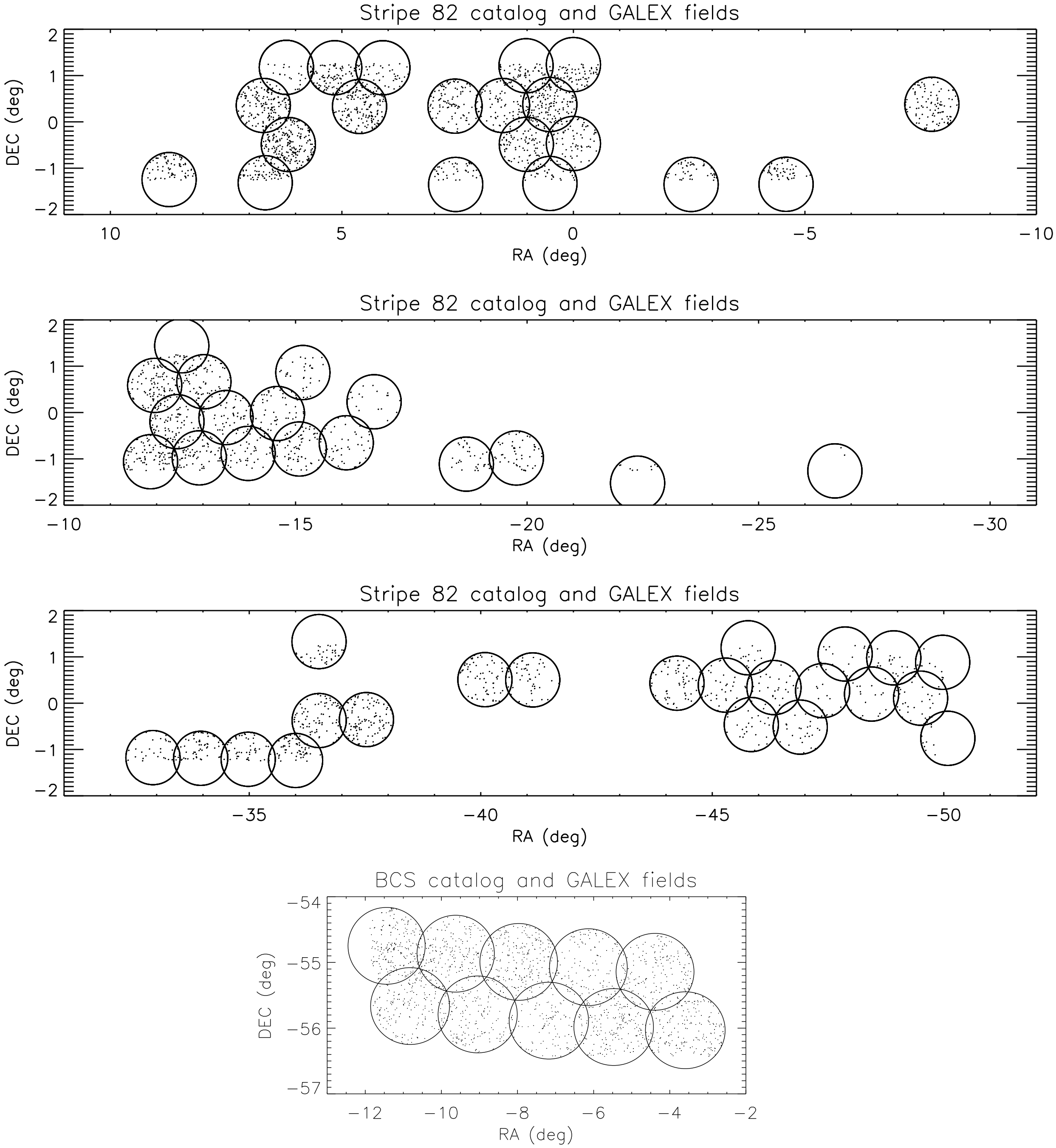


FIG. 5.— QSO candidates location in the sky both in the Stripe-82 field (upper panel) and the BCS 23-hour field (bottom panel). Blank regions currently lack GALEX observations.

BCS 23-hour region is one of the lowest extinction areas in the sky, which allows for deeper GALEX observations than in the Stripe 82 and a higher rate (50-100%) at finding QSO candidates. In fact, for the BCS 23-hour region we find $\sim$ 100QSO's/sq. deg. which is similar to the QSO density found by Richards et al.

Table 2 shows the header of the catalog available online (`www.ice.csic.es/personal/jimenez/PHOTOZ`) and describes the different entries for the catalog. We give the maximum likelihood redshift using the method described in Niemack et al. (2008) and the corresponding optical magnitudes in each survey. On the web page we provide catalogs for the two different magnitude cuts ($i < 20$ and $i < 21.5$). These catalogs will be updated on-line as our GALEX observations are completed.

## 4. CONCLUSIONS

We have constructed a new catalog of photometric QSO candidates from GALEX photometry and optical $r$-band data. In the SDSS Stripe 82 field, our selection criteria is successful in finding true QSO's at the 60% (30%) level with $i < 20$ ($i < 21.5$) when compared with the Richards et al. (2008) QSO catalog constructed using 5-band optical SDSS photometry. Comparison with the same catalog by Richards et al. shows

TABLE 2
Description of columns in the SCS-QSO catalog. ML z refers to the best maximum lieklihood photo-z estimate as described in Niemack et al. (2008). The catalog is available at `http://www.ice.csic.es/personal/jimenez/PHOTOZ`.

| Col. number | Description |
|---|---|
| 1 | SDSS-Cmodel u |
| 2 | SDSS-Cmodel g — BCSmagauto g |
| 3 | SDSS-Cmodel r — BCSmagauto r |
| 4 | SDSS-Cmodel i — BCSmagauto i |
| 5 | SDSS-Cmodel z — BCSmagauto z |
| 6 | NUVmagauto |
| 7 | FUVmagauto |
| 8 | ML z |
| 9 | GALEX RA (deg) |
| 10 | GALEX DEC (deg) |
| 11 | GALEX objects within search radius |
| 12 | Optical galaxies matched to GALEX object |

that the completeness of the sample is 40%(25%). For low extinction regions our completeness grows to 95%. This catalog covers some of the areas currently being scanned by microwave Sunyaev-Zeldovich experiments. It therefore provides a point source catalog to be masked out in these experiments. It can also be used to cross-correlate QSO positions with microwave temperature fluctuations to detect the Sunyaev-Zeldovich distortions due to the energy ejection from quasars into the surrounding intergalactic medium (Chatterjee & Kosowsky 2007, 2008; Scannapieco et al. 2008). Even at medium depth, GALEX coverage will have substantial utility in combination with optical imaging programs like Pan-STARRS (which does not have $u$ band coverage). We anticipate that a GALEX observation program covering the SZ survey areas at medium depth in combination with single $r-$band photometry will be extremely useful to the SZ community. New QSO catalogs will also enable further studies including absolute astrometric reference frames.

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